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The case for a near-term commercial demonstration of the Integral Fast Reactor

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ABSTRACT

Demonstrating a credible and acceptable way to safely recycle 'used' nuclear fuel will clear a socially acceptable pathway for nuclear fission to be a major low-carbon energy source for this century. Here we advocate for an accelerated timetable for commercial demonstration of Generation IV nuclear technology, via construction of a prototype metal-fueled fast neutron reactor and associated 100 t/year pyroprocessing facility to convert and recycle spent fuel (routinely mischaracterized as "nuclear waste") that has accumulated from decades of light-water reactor use. Based on the pioneering research and development done during the 'Integral Fast Reactor' (IFR) program at Argonne National Laboratory,[1] a number of synergistic design choices are recommended: (a) a pool-type sodium-cooled reactor; (b) metal fuel based on a uranium–plutonium–zirconium alloy, and (c) recycling using electrorefining and pyroprocessing, thereby enabling the transmutation and repeated re-use of the actinides in the reactor system. We argue that alternative technology options for the coolant, fuel type and recycling system, while sometimes possessing individually attractive features, are challenging to combine into a sufficiently competitive overall system. A reactor blueprint that embodies these key design features, the General Electric-Hitachi 380 MWe PRISM,[2] based on the IFR, is ready for a commercial-prototype demonstration. A two-pronged approach for completion by 2020 could progress by a detailed design and demonstration of a 100 t/year pyroprocessing facility for conversion of spent oxide fuel from light-water reactors[3] into metal fuel for fast reactors, followed by construction of a prototype PRISM as a commercial-scale demonstration plant, with an initial focus on secure disposition of separated plutonium stocks. Ideally, this could be achieved via an international collaboration. Several countries have expressed great interest in such collaboration. Once demonstrated, this prototype would provide an international test facility for any concept improvements. It is expected to achieve significant advances in reactor safety, reliability, fuel resource sustainability, management of long-term waste, improved proliferation resistance, and economics.

1. Introduction

When contemplating the daunting energy challenges facing humanity in the twenty-first century in a world beyond fossil fuels, there are generally two schools of thought [1]. One is to take a scattergun approach, which emphasizes energy efficiency, a gamut of actual and potential clean, low-carbon energy systems, and a hope of future technological advances to solve currently intractable problems like large-scale energy storage. Those who espouse such a view sometimes admit that a large component of natural gas will be needed to 'fill the gaps' and often support the view that the majority of humanity will have to learn to be content with consuming much less energy than the customary level common in developed countries [2,3]. The other perspective sees a way out of the climate/energy/population dilemma in the development and deployment of environmentally benign, fit-for-service technologies that can provide the vast amounts of energy that will be (and are being) demanded, over many millennia into the future [4,5]. This view not only recognizes that people who are accustomed to energy wealth (or aspire to it) will be loath to give it up, but that there will be no reason to do so. In fact, vast amounts of energy will be required in order to rectify the damage already done to the environment, and to avoid further damage and resource depletion in the future [6].

The latter viewpoint—sometimes referred to pejoratively by proponents of energy asceticism as the 'techno-fix' mindset—is nevertheless

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[1] http://www.ne.anl.gov/About/reactors/frt.shtml.
[2] http://www.ge-energy.com/content/multimedia/_files/downloads/dataform_2053733743_2809794.pdf.
[3] http://www.thesciencecouncil.com/pdfs/PyroprocessingBusinessCase.pdf.

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a pragmatic one, given the scale of the energy replacement challenge. Here we outline arguments for the necessary design attributes of a successful sustainable nuclear energy system—one that could be feasibly deployed within this decade; we also explore ways in which international cooperation can be mustered to move as quickly as possible from the experimental to the commercial phase.

2. Partner nations preparing today for tomorrow's energy needs

At the turn of the twenty-first century a group of nine nations agreed to collaborate in the development of advanced nuclear power systems capable of meeting the energy needs and aspirations of the new millennium. These nine nations were soon joined by several other countries to form the *Generation IV International Forum*, GIF.[4] (Generation IV refers to the next-generation nuclear power systems in the incremental technical evolution—Generation I through III—since the dawn of the nuclear age.[5])

The goals of GIF involved four categories: sustainability, economics, safety and reliability, and proliferation resistance and physical protection. Six promising nuclear technology concepts were selected after an initial evaluation of a wide variety of systems, with an aspiration for ongoing development to 2030 and beyond. (In an evaluation of 19 reactor systems by the Gen IV Roadmap Integration Team in 2002, the "Integral Fast Reactor" system [detailed in a later section] ranked number one overall.[6]). Until recently, deployment of fast reactor systems was characterized as plausible only decades into the future. Yet this statement is belied by the fact that Russia has been running commercial oxide-fueled fast reactors for decades, with the most recent incarnation being the BN-600; furthermore, new fast reactor systems are integral parts of the energy planning in countries such as India (the three-stage nuclear program), Russia, China and South Korea [7]. And in terms of government–private partnerships, in November of 2011 GE-Hitachi Nuclear made a paradigm-shifting offer to the United Kingdom, which was seeking a solution to disposition of that nation's plutonium inventory[7] (at 112 tons, the largest such stockpile in the world). GEH submitted an offer to build a pair of PRISM reactors in the UK to solve their plutonium quandary in about five years, with the recouping of costs coming via a set fee for each kilo of plutonium that was successfully processed by the PRISMs[8] and from the electric power generated in the process.

Given the pressing nature of climate change, burgeoning population growth, regional conflicts of fossil-fuel supply, and the socio-political imperative to demonstrate solutions to the perceived problems of current-generation nuclear energy systems, it seems clear that the international community is in urgent need of a way to cut through the interminable delays in the commercial deployment of 'next-generation' nuclear technology.

3. The Integral Fast Reactor system design

The Integral Fast Reactor (IFR) is a Generation IV system that meets the goals of GIF squarely and comprehensively, being backed by decades of engineering-scale R&D at Argonne National Laboratory and elsewhere [8,9}. The IFR is ready for commercial demonstration. It has the following essential features: (a) liquid sodium coolant, (b) pool configuration, (c) metallic fuel, and (d) fuel recycling using pyroprocessing.[9] The term "integral" as in "IFR" refers to the on-site reprocessing aspect of the spent fuel. (See Fig. 1.)

Liquid sodium coolant has by far the most operational experience in fast reactor systems worldwide [10], and offers a number of advantages compared to alternative fast reactor coolants such as lead, lead–bismuth eutectics (LBE) or gas (e.g., carbon dioxide, helium): it transfers heat from the fuel with superlative efficiency; it can absorb significant heat without excessive temperature rise; its boiling point is far above operating temperatures (when operated in synergy with metal rather than oxide fuels, as detailed in the next section), yet it melts at a fairly low temperature; it does not react chemically with either the reactor structural materials or the metallic fuel; it is stable both chemically and under irradiation; its activation products are short-lived; and finally, it is cheap and commonly available. These attributes allow operation of the fast neutron reactor at atmospheric pressure, a characteristic that has many obvious safety and structural advantages [11]. The main disadvantages of sodium are its opacity and its high chemical reactivity with oxygen in water or air [12]. These disadvantages are overcome by design and, regarding sodium's opacity, new imaging technologies that can be used to inspect components immersed in the coolant. Also, although the conductivity of sodium is very high, its volumetric heat capacity ($J/m^3 - K$) of sodium is slightly lower than competing liquid metal coolant options (lead, LBE) and almost four times lower than that of water. Thus sodium has no advantage for heat removal for a given volumetric flow rate, but its lower density does give it an edge through lower pressure drop and pumping power than for lead and LBE.

The reactor pool has both primary and secondary guard vessels with no penetrations below the sodium surface level, to minimize the possibility of leakage, with the gap between the vessels filled by inert argon gas. This configuration makes it simple to isolate the radioactive primary coolant from the steam generator [8]. A non-radioactive secondary sodium circuit gives up its heat to the steam generators in a separate structure away from the reactor core, and if leakage does occur it would leak slowly out of any pipe break because the circuit is not pressurized. The reactor pool contains enough sodium to absorb the transient heat under accident conditions, to allow safe reactor regulation, and to permit passive circulation and heat removal.

The metal fuel, a ternary alloy of uranium–plutonium–zirconium, is a crucial choice for the IFR.[10] The long-standing problem of fuel swelling that plagued early use of metal fuel and severely limited fuel burnup was solved by allowing the fuel slugs to fit loosely within the stainless steel cladding, with the necessary thermal bond provided by a sodium filler between fuel and cladding [13]. Fission-product gases are collected in a plenum above the fuel. This simple innovation allows for long irradiation times and high burnup (once fuel swells to the cladding's inner surface, fission-gas pores interconnect and the gas is released to the plenum without further swelling). The metal fuel not only allows for high breeding ratios and a simple yet proliferation-resistant method of recycling and recasting (see below); it also confers significant safety features. Little heat energy is stored in the fuel (tied to the higher thermal conductivity of the metallic fuel as compared to oxide fuel) and is rapidly transferred to the sodium coolant; furthermore, negative reactivity feedbacks occur as core temperature rises, quickly reducing reactivity due to increased neutron leakage. The low stored energy in the metal fuel means that there is no energetic fuel-coolant interaction, even after (hypothetical) sheath rupture and intimate mixing of fuel and sodium [8]. Also, cladding failure does not propagate with metal fuel because of the limited chemical interaction between metal fuel and sodium.

The pyroprocess for fuel recycling uses an electrochemical system to separate actinides from the fission product waste within a hot molten-salt bath, yet it cannot yield a purified plutonium stream (the pyroprocessing heavy-metal product is inevitably mixed with minor actinides and highly radioactive trace lanthanides, providing substantial self-protecting proliferation resistance [14]). The fission products are immobilized in zeolite and vitrified, while the actinides can be readily re-formed into metal fuel pins using a simple injection-casting method that can be done remotely [11]. The pyroprocess lends itself to a very

4 http://www.gen-4.org/Technology/systems/index.htm.
5 http://www.gen-4.org/Technology/evolution.htm.
6 http://thesciencecouncil.com/pdfs/RankingOf19ReactorSystems.pdf.
7 http://www.nda.gov.uk/strategy/nuclearmaterials.
8 http://www.guardian.co.uk/environment/2012/jul/09/nuclear-waste-burning-reactor.
9 http://www.thesciencecouncil.com/energy-the-fast-reactors-promise.html.

10 Other minor actinides (of various isotopic compositions) could plausibly be substituted for, or mixed with, the plutonium, but the U–Pu–Zr alloy is the demonstration design.

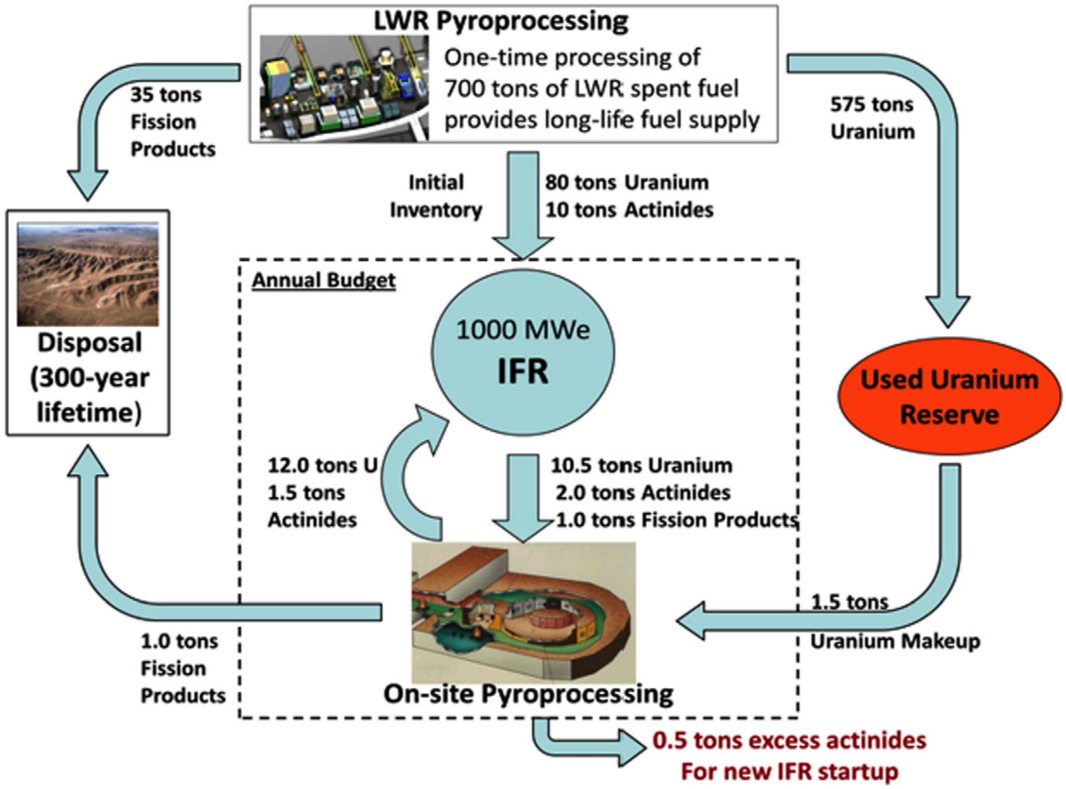

Fig. 1. Mass-flow diagram for an electrorefining-pyroprocessing facility using light-water reactor (LWR) waste to provide fuel for a gigawatt-sized integral fast reactor (IFR) plant operating in closed-cycle mode.

compact plant design (in a batch process) without aqueous byproducts, thereby offering significant potential cost savings and environmental benefits. It also does not suffer from the continuous threat of inadvertent criticality. This is of particular importance for fast-reactor fuel with fissile content of up to 20%. Aqueous reprocessing of fuel with this high fissile content will require constant attention and great care, as well as special design measures (e.g., long thin vessels).

The reason for recommending these design choices in preference to potential fast reactor alternatives (e.g., oxide fuel, lead coolant or loop configuration), are reviewed in great detail by Charles Till & Yoon Chang, who were principal designers and engineers on the IFR project, in the authoritative book *Plentiful Energy* [15].

In summary, the key design elements of the IFR — metallic fuel, sodium coolant and pool vessel configuration, work together as a complementary system to bring out the best in the fast reactor and yield many desirable, synergistic characteristics. These component choices, along with the associated proliferation-resistant and relatively inexpensive process for recycling the used fuel and the technology for disposal of the residual waste, define an advanced nuclear system that can truly be called revolutionary in its possibilities. In the words of the Nobel laureate physicist Hans Bethe, "All the pieces fit together."

Next-generation nuclear energy, as exemplified by the IFR design, offers a means to produce vast quantities of zero-carbon and reliable electricity and process heat [16,17]. By taking advantage of the superior physical properties of plutonium in a fast-neutron spectrum for converting essentially all of the mined uranium into useful fissile material, the IFR can change in a fundamental way the outlook for global energy on the necessary massive scale.[11] These resource extension properties multiply the amount of usable fuel by a factor of over a hundred, allowing demand to be met for many centuries with fuel already at hand, by a technology that is known today, and whose properties are largely established. (In a setup optimized for breeding of fissile material, to be used as the startup inventory of new IFRs, an optimized compound system doubling time has been estimated to be approximately 8.5 years [18]). David MacKay [19], until recently the chief science advisor to Great Britain's Dept. of Energy & Climate Change, has been reported in the British press as saying that if the UK were to build IFR systems to power that country, enough fuel is already available to make the UK energy independent for 500 years.[12] All that is required now is to complete the final steps in a prototype demonstration to give confidence for a large-scale deployment.

4. Alternative technology choices and implications

The GIF selected six promising next-generation nuclear technologies on which to focus for research, development and deployment. Some of them have the benefit of actual experimental experience, while others are yet theoretical. In considering the subset of reactor types and components that might be selected and integrated for a prototype next-generation nuclear demonstration plant, it is crucial that the overall goals of the GIF be met, and that it can be demonstrated at a commercial scale now, since climate change, population growth and other critical issues for achieving 21st century sustainability will not wait for long-term research and development. Replacement of fossil fuels is urgently needed to sustain our planet's well-being.

We should clarify at this point that construction of advanced water reactor designs is imperative to meet the near-term electricity demand growth. Light-water reactors (LWR) of any design, however, can harness only a tiny fraction of the potential energy in uranium, less than 1% (even with plutonium recovered via aqueous reprocessing) [20]. Fast reactors, by contrast, can unlock nearly all of uranium's stored energy if coupled with an iterative fuel recycling system [21].

[11] http://www.sacome.org.au/images/stories/Nuclear_Series_SA_Mines__Energy_Journal.pdf.

[12] http://www.theguardian.com/environment/2012/feb/02/nuclear-reactors-consume-radioactive-waste.

Indeed, the IFR, with its metal-fuel system and electrorefining via pyroprocessing, is able to utilize the actinides to such a degree as to not only extend the usable fuel supply by more than an order of magnitude, but also to essentially solve the waste problem by reducing the radiological toxicity of the waste products from hundreds of thousands of years to a mere few hundred years [8]. Even if the "million-year problem" of LWR spent fuel is more a political than a technical challenge (given the small volume of the waste stream), nevertheless the issue of public perception of that issue is the one that guides nuclear policy in many countries [22]. As such, the transition to fast reactors and a closed nuclear fuel cycle are both a technical advancement and a political enabler for nuclear power of all kinds.

Of the other fast reactor systems besides the IFR/PRISM that are in the R&D phase in various countries today, it is important to weigh the pros and cons vis-à-vis IFRs. This includes consideration of alternative coolants, such as lead, and fuel forms such as uranium nitride or oxide. For reasons explained above and detailed elsewhere [15], we argue that the use of sodium coolant and metal fuel, within an IFR-like system, is likely to yield the optimal outcome in terms of operational efficiency and inherent safety. However, one of the issues most often mentioned when discussing sodium-cooled fast reactors—by far the type with the most reactor-years of experience worldwide—is the chemical reactivity of sodium, which burns upon contact with air (though with a cool flame) and reacts vigorously upon contact with water [12]. Yet, despite this, and sodium's lower boiling point and volumetric heat capacity compared to other metal coolants, sodium actually has several compelling advantages in fast-reactor operation, especially when coupled to metal fuels. Sodium has superior heat-exchange properties (unlike gas coolants), virtually no corrosive effect on reactor components even after decades of operation (unlike lead), a low melting point (so less likely to freeze, compared to lead), and a short half-life of sodium isotopes that form in the reactor vessel, etc. (unlike lead). Some advocates of other systems characterize sodium's volatility as a deal-breaker. But the intermediate loop that transfers heat from the reactor vessel to the steam generator contains only non-radioactive sodium, with the steam generator isolated in a separate structure, assuring that in the highly unlikely event of a sodium-water reaction there will be no danger to the primary system and no chance of radioactive material being involved [8]. This design means that the unfairly characterized sodium problem is nothing more than an engineering design issue, involving a common element that has been used in industrial processes for well over a century. With over 300 reactor-years of experience with sodium-cooled fast reactors around the world, not a single instance of sodium-water interaction resulting in radioactive release has been recorded.[13]

We note that a range of other fast reactor and thermal reactor systems are being investigated today, having reached various stages of development [23]. This includes molten fluoride salt thorium reactors (LFTRs) and liquid-salt-cooled pebble fuel systems[14] [5]. While some of these seem to hold promise, none are near the level of readiness for near-term commercial-prototype deployment as the PRISM reactor and its metal-fuel technology. In addition, none of the immediate prospects can match the IFR concept in meeting all the goals of the Gen IV initiative.

5. The way forward

It is imperative that we seek to displace our heavy dependence on fossil fuels over the coming decades with sustainable, low-carbon alternative energy sources that can provide reliable, economic baseload electricity and heat, and thereby mitigate the environmental damage of energy production and underpin global energy security and prosperity for a growing population [16,24]. So how best to proceed?

Here we argue that without an economically viable closed fuel cycle, there will be no dominant nuclear future. Modern technology is already capable of building fast reactors, but we do not have all problems solved on the fuel cycle side. Given this reality, there is now a pressing need to demonstrate a credible and acceptable way to safely deal with used nuclear fuel in order to clear a socially acceptable pathway for nuclear fission to be a major low-carbon energy source for this century [1]. Given the enormous technical, logistical and economic challenges of adding carbon capture and storage to coal and gas power plants, we are faced with the necessity of a nearly complete transformation of the world's energy systems. Objective analyses of the inherent constraints on wind, solar, and other less-mature renewable energy technologies inevitably show that they will fall woefully short of meeting future low-emissions demands [19,25]. A 'go slow, do little' approach to energy policy is not defensible given the urgency of the problems society must address, and the time required for an orderly transition of energy systems at a global scale. As such, we advocate a near-term commercial-scale deployment of the Integral Fast Reactor.

What is needed now is a two-pronged approach, for completion by 2020 or earlier, that involves: (i) demonstration of the pyroprocessing of LWR spent oxide fuel, and (ii) construction of a PRISM fast reactor as a prototype demonstration plant, to establish the basis for licensing and the cost and schedule for subsequent fully commercial IFR plants.[15] Once demonstrated, this commercial IFR will be expected to show significant advances in nuclear safety, reliability, nuclear fuel sustainability, management of long-term waste, proliferation resistance, and economics.

The time has come to capitalize on this exceptional energy technology, with the benefits of this development extending throughout the global energy economy in the 21st century [16,26]. When coupled with the near-term deployment of other cutting-edge technologies, such as zero-emission vehicles and plasma recyclers, modern society will be within reach of eliminating most air pollution, recycling spent nuclear fuel, and bringing the fossil fuel era to an end. This will serve to prevent resource wars (including potential water wars), effortlessly recycle virtually all of our waste products, power our vehicles with zero-emission energy systems, provide abundant energy and fresh water to every nation, reduce human-caused greenhouse gas emissions to a trickle, diminish the world's nuclear arsenals, turn old nuclear weapons into energy, and promote other technologies that, once commercialized and deployed on a large scale, can lead us to a sustainable post-scarcity era. It is a long-term vision worth striving for, but it starts with tractable near-term goals.

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